Appendix A

Phase II, Phase III, and Phase IV Turbine Parameters

Basic Machine Parameters

- Number of Blades: 3
- Rotor diameter: 10.046 m (10.1 m for Phase II)
- Hub height: 17.03 m
- Type of rotor: fixed
- Rotational speed: 71.63 rpm synchronous speed
- Cut-in wind speed: 6 m/s (tests were run at lower speeds)
- Power regulation: stall
- Rated power: 19.8 kW
- Tilt: 1° (blade pitch angle was calibrated assuming 0° tilt)
- Cone angle: 3.417°
- Location of rotor: downwind
- Rotational direction: clockwise (viewed from downwind)
- Rotor overhang: 1.32 m (yaw-axis to center of rotation of rotor).

Rotor

Geometry

- Blade cross-section and planform:
  - Phase II: NREL design (Constant chord, no taper, no twist)
  - Phase III and IV: NREL S809 (Constant chord, no taper, optimally twisted)
- Root extension: 0.723 m
- Blade pitch angle (manually set by turbine operator):
  - Phase II: 12 degrees
  - Phase III: 3 degrees
  - Phase IV: -9°, -3°, 3°, 8°, and 12° (see each data file).
- Blade profile: NREL S809
- Blade chord: 0.4572 m at all span stations
- Blade twist:
  - Phase II: untwisted
  - Phase III and IV: see Table A.1.

Table A.1 Blade Twist

Radius from Rotor Center (m)	Twist (°)
0.724	44.67
0.880	39.39
1.132	32.29
1.383	26.56
1.634	21.95
1.886	18.19
2.137	15.10
2.389	12.52
2.640	10.35
2.892	8.50
3.143	6.91
3.395	5.52
3.646	4.32
3.897	3.25
4.149	2.30
4.400	1.45
4.652	0.69
4.903	0.00

(Composite Engineering, 1994)

- Blade thickness:
  - Phase II:
    - At 14.4% span: t = 43% chord (span refers to rotor center)
    - Between 14.4% and 30.0% span the thickness decreases linearly
    - At 30.0% span: t = 20.95% chord
    - Outboard of 30.0% span: t = 20.95% chord
  - Phase III and IV:
    - At 14.4% span: t = 43.0% chord (span refers to rotor center)
    - Between 14.4% and 25.0% span the thickness decreases linearly
    - At 25.0% span: t = 20.95% chord
    - Outboard of 25.0% span: t = 20.95% chord
- Airfoil distribution: Except for the root, the blade uses the S809 at all span locations. The airfoil coordinates are shown in Table A.2. In the root sections the airfoil shape is altered by the enlarged spar. This enlargement is a virtually perfect circle (in cross section) at the root which is centered at the quarter chord. The thickness of the spar area enlargement varies from this maximum at the root to a thickness that fits inside the airfoil profile at the 30% span (and outboard). In between the root and 30% span the spar area enlargement is flattened into consecutively thinner and thinner elliptic shapes, but each ellipse has a perimeter equal to the circumference of the base circle. The twisted blade used in Phases III and IV is similar, except that the spar enlargement fits within the airfoil at 25% span. Figure A.1 illustrates the blade surface in the root region.

Table A.2. Airfoil Profile Coordinates

Upper Surface		Lower Surface	
x/c	y/c	x/c	y/c
0.00037	0.00275	0.00140	-0.00498
0.00575	0.01166	0.00933	-0.01272
0.01626	0.02133	0.02321	-0.02162
0.03158	0.03136	0.04223	-0.03144
0.05147	0.04143	0.06579	-0.04199
0.07568	0.05132	0.09325	-0.05301
0.10390	0.06082	0.12397	-0.06408
0.13580	0.06972	0.15752	-0.07467
0.17103	0.07786	0.19362	-0.08447
0.20920	0.08505	0.23175	-0.09326
0.24987	0.09113	0.27129	-0.10060
0.29259	0.09594	0.31188	-0.10589
0.33689	0.09933	0.35328	-0.10866
0.38223	0.10109	0.39541	-0.10842
0.42809	0.10101	0.43832	-0.10484
0.47384	0.09843	0.48234	-0.09756
0.52005	0.09237	0.52837	-0.08697
0.56801	0.08356	0.57663	-0.07442
0.61747	0.07379	0.62649	-0.06112
0.66718	0.06403	0.67710	-0.04792
0.71606	0.05462	0.72752	-0.03558
0.76314	0.04578	0.77668	-0.02466
0.80756	0.03761	0.82348	-0.01559
0.84854	0.03017	0.86677	-0.00859
0.88537	0.02335	0.90545	-0.00370
0.91763	0.01694	0.93852	-0.00075
0.94523	0.01101	0.96509	0.00054
0.96799	0.00600	0.98446	0.00065
0.98528	0.00245	0.99612	0.00024
0.99623	0.00054	1.00000	0.00000
1.00000	0.00000	0.00000	0.00000

(Butterfield et. al, 1992)

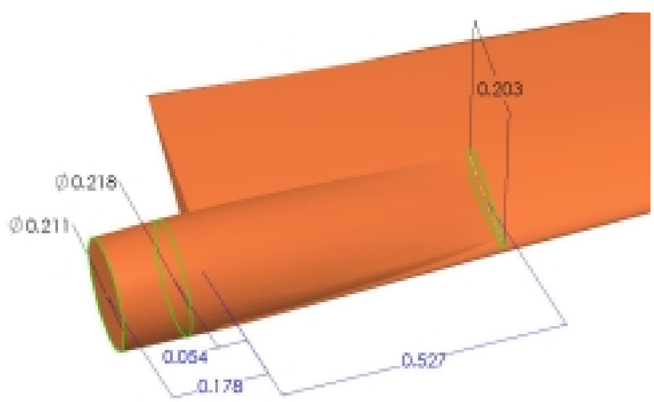

Figure A.1. Twisted blade root surface depiction (dimensions in meters).

Aerodynamics for S809 Airfoil

- Performance coefficients (α = angle of attack; C_l = lift coefficient, C_{dp} = pressure drag coefficient) obtained at the Colorado State University wind tunnel with a Reynolds number of 500,000 are shown in Table A.3 (Butterfield et al. 1992; For additional wind tunnel measurements, see Somers 1997).

Table A.3. Wind Tunnel Profile Coefficients

α	C_l	C_{dp}
-2.23	-6.00E-02	6.00E-03
-1.61E-01	1.56E-01	4.00E-03
1.84	3.69E-01	6.00E-03
3.88	5.71E-01	8.00E-03
5.89	7.55E-01	9.00E-03
7.89	8.60E-01	1.70E-02
8.95	8.87E-01	2.40E-02
9.91	8.69E-01	3.50E-02
10.9	8.68E-01	3.90E-02
12	8.94E-01	4.80E-02
12.9	9.38E-01	6.10E-02
14	9.29E-01	7.40E-02
14.9	9.08E-01	8.00E-02
16	9.12E-01	1.06E-01
17	6.55E-01	2.71E-01
18	5.88E-01	2.65E-01
19	5.87E-01	2.81E-01
20	5.97E-01	2.99E-01
22	6.03E-01	3.26E-01
24	6.47E-01	3.75E-01
26	6.83E-01	4.19E-01
28.1	7.45E-01	4.82E-01
30	8.24E-01	5.60E-01
35	1.05	8.17E-01
40	1.14	1.03
45	1.2	1.26
50	1.12	1.38
55	1.17	1.7
60	1.08	1.87
65	9.40E-01	1.98
70	8.57E-01	2.19
74.9	6.66E-01	2.17
79.9	4.72E-01	2.21
84.8	3.56E-01	2.32
89.9	1.42E-01	2.09

Structural Properties

- Rotor mass:
  - Phase II: 147.7 kg + 13 kg root mounted camera
  - Phase III: 215.1 kg
  - Phase IV (1996): 204 kg
  - Phase IV (1997): 206.5 kg.
- Hub mass:
  - Phase II: 269.1 kg (includes 3 instrumentation boxes, boom, camera)
  - Phase III: 236.3 kg (includes 3 instrumentation boxes
  - Phase IV (1996 and 1997): 288.3 kg (includes 3 instrumentation boxes, boom, camera) Figure A.2 depicts the hub-mounted instrumentation boxes, the boom and the camera that were implemented in Phase IV testing.

Figure A.2. Hub-mounted instrumentation boxes, boom, and camera.

- Blade material: Fiberglass/epoxy composite
- Blade mass (outside root):
  - Phase II:
    - Blade 1: 49.3 kg
    - Blade 2: 49.5 kg
    - Blade 3: 48.9 kg (not including root mounted camera. This caused a rotor imbalance).
  - Phase III: 71.7 kg (each blade, including root mounted camera. The cables that extend from the instrumented blade were wrapped around the root of the blade when the three blades were balanced. When the cables were routed to the hub upon installation, the blades masses were no longer balanced).
  - Phase IV (1996): 68 kg (each blade, including root mounted camera)
  - Phase IV (1997):
    - Blade 1: 68.8 kg
    - Blade 2: 68.8 kg
    - Blade 3: 68.9 kg (including root mounted camera).

- Blade center of gravity (from the root):
  - Phase II:
    - Blade 1: 1.63 m
    - Blade 2: 1.68 m
    - Blade 3: 1.61 m.
  - Phase III: 1.58 m (all blades)
  - Phase IV (1996): 1.53 m (all blades)
  - Phase IV (1997):
    - Blade 1: 1.51 m
    - Blade 2: 1.50 m
    - Blade 3: 1.50 m.
- Blade mass and stiffness distributions
  - Phase II: The root stiffness was measured by the strain gages, and the blade mass and stiffness distributions were estimated in Simms and Butterfield (1991) as shown in Table A.4. The root mounted camera (13 kg) was not included in the mass distribution.

Table A.4. Phase II, Untwisted Blade, Structural Properties.

Distance from Rotor Center (m)	Mass (kg/m)	Edgewise Stiffness (Nm^2)	Flapwise Stiffness (Nm^2)
5.030	5.59	37939	417556
4.527	5.59	37939	417556
4.024	6.57	49992	480118
3.521	7.29	61815	537514
3.019	8.02	73180	492614
2.516	8.75	84200	644844
2.013	9.72	95019	697074
1.510	12.14	115567	798091
1.007	17.00	406938	1169444
0.750	17.98	743278	998403
0.529	17.98	1369469	1439779
0.402		473517	473517

  - Phase III and IV: Estimates of mass and stiffness distributions were made by the blade manufacturer (Composite Engineering 1994). The pressure instrumentation and counterweights were included, as well as the root mounted camera.

Table A.5. Phase III and IV, Twisted Blade, Structural Properties.

Distance from Rotor Center (m)	Mass (kg/m)	Edgewise Stiffness (Nm^2)	Flapwise Stiffness (Nm^2)
5.029	9.32	46953	365070
4.526	9.25	46953	387600
4.023	10.22	65974	436440
3.520	11.19	84468	512420
3.018	12.06	105560	583420
2.515	12.95	123480	650900
2.012	13.49	149420	737010
1.509	16.92	232180	997640
1.006	46.09	710230	1332800
0.749	45.18	1302400	1556800
0.508	30.14	2320700	2322100
0.402		473517	473517

- First edgewise eigenfrequency:
  - Phase II: 8.75 Hz
  - Phase III and IV:
    - Non-instrumented blade: 8.16 Hz, 0.84% damping
    - Instrumented blade: 7.97 Hz, 0.69% damping.
- First flapwise eigenfrequency:
  - Phase II: 4.70 Hz
  - Phase III and IV:
    - Non-instrumented blade: 4.94 Hz, 0.9% damping
    - Instrumented blade: 4.79 Hz, 0.95% damping.

Power Train

Layout

- The power train consists of the rotor mounted on a low-speed shaft coupled to a high-speed shaft via a gearbox. The high-speed shaft couples directly to an induction generator. The mechanical brake is positioned on the high-speed shaft.

Characteristics

- Rotor inertia: 1356 kg m^2 w.r.t. low-speed shaft; includes boom and instrumentation boxes used in Phase IV configuration
- Inertia of rotating system (rotor, low-speed shaft, gearbox, high-speed shaft): 1535 kg m^2 w.r.t. low-speed shaft; includes boom and instrumentation boxes used in Phase IV configuration
- Gearbox ratio: 25.13:1
- Gearbox inertia: Not available
- Gearbox stiffness: Not available
- Gearbox suspension stiffness: Not available
- Gearbox suspension damping: Not available
- High-speed shaft inertia: Not available

- High-speed shaft damping: 0.5% to 1.0%
- High-speed shaft stiffness: Not available
- Generator inertia: 143 kg m^2 w.r.t. low-speed shaft
- Generator slip: 1.59% at 20 kW
- Generator time constant: < 0.025 seconds (electro-mechanical time constant, for generator only)
- Frequency of drive train: Not available
- Power train efficiency:
  - Gearbox: 97%
  - Windage, couplings, main shaft bearings: 98%
  - Generator: The efficiency curve (in %) of the combined system (gearbox + generator) versus generator power (kW) is a sixth order polynomial as follows:

    $$Eff = (-1.9717\cdot 10^{-5})\cdot P_{gen}^{6} + (1.5989\cdot 10^{-3})\cdot P_{gen}^{5} + (-5.1150\cdot 10^{-2})\cdot P_{gen}^{4} + (8.2486\cdot 10^{-1})\cdot P_{gen}^{3} + (-7.1329\cdot 10^{0})\cdot P_{gen}^{2} + (3.2622\cdot 10^{1})\cdot P_{gen} + (9.2674\cdot 10^{0}).$$

    Thus, the efficiency is fairly constant at about 78%.
- The low-speed shaft torque measurement requires a correction due to calibration errors in the Phase II and Phase III data as follows:
  - Phase II: $T_{corr} = 1.08\cdot T_{measured}+15.16$
  - Phase III: $T_{corr} = 0.97\cdot T_{measured}-196.43$
- Maximum brake torque: 115.24 Nm
- The inertia of the low-speed shaft + gearbox + high-speed shaft may be found by subtracting the rotor inertia from that of the rotating system.
- The stiffness of the low-speed shaft, gearbox, and high-speed shaft as a lumped parameter is $1.70\cdot 10^{5}$ Nm/rad.

Tower

Description

- Basic description: two different diameter cylinders connected by a short conical section. The conical section base is 5.385 m above the ground. The conical section top is 6.300 m above the ground. The tower is further supported by 4 guy wires attached 11.91 m above the ground. The guy wires descend to the ground at an angle 44.3 degrees below horizontal. The ground anchors for the four wires are at the following compass directions from the tower axis: 90°, 180°, 270°, and 360°.

Characteristics

- Tower material: 9.525 mm Corten steel
- Tower height: 15.9 m
- Tower diameter(base): 0.4572 m
- Tower diameter(top): 0.4064 m
- Tower mass: 1481 kg
- Tower head mass: 1279 kg (hub and nacelle)
- Position of tower head c.g.: Not available
- Bending spring constant: 48118 N/m

- Torsional stiffness: Not available
- Torsional damping: Not available
- Nacelle inertia: 1211 kg m^2
- First tower bending eigenfrequency (x): 5.49 Hz, 1.22% damping
- First tower bending eigenfrequency (y): 5.71 Hz, 1.49% damping
- First tower torsion eigenfrequency: Not available
- First tower/nacelle eigenfrequency (x): 1.95 Hz, 1.87% damping
- First tower/nacelle eigenfrequency (y): 1.94 Hz, 2.10% damping.

Full-System Modal Analysis

Table A.6: Phase II, Untwisted Blades, Including Instrumentation Boxes, Boom and Camera; Phase IV, Twisted Blades, Including Instrumentation Boxes, Boom and Camera; Blade 3 at 0°, Blade 1 at 120°, and Blade 2 at 240°.

Mode Shape Description	Phase II Frequency and Damping	Phase IV Frequency and Damping
Tower top bending, side-to-side		1.59 Hz 0.05%
Tower top bending, fore-aft Nacelle and rotor translating	1.7427 Hz 3.213%	1.72 Hz 0.75%
Nacelle yaw, blades move rigidly		2.22 Hz 5.74%
First out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase, coupled with nacelle pitch and tower fore-aft	3.424 Hz 1.773%	3.69 Hz 1.78%
First out of plane blade bending, symmetric, nacelle translating	4.029 Hz 1.591%	5.02 Hz 2.57%
First out of plane blade bending, blades 1 & 2 asymmetric, blade 3 in torsion, nacelle yaw and tower torsion	2.495 Hz 2.962%	5.32 Hz 2.69%
First out of plane blade bending, symmetric. First in plane bending, blades 1 & 3 move toward each other, blade 2 low in-plane motion. Nacelle pitch	5.555 Hz 1.531%	5.77 Hz 4.13%
First out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 2 & 3 move towards each other, blade 1 low motion		6.43 Hz 4.77%
Tower bending side to side as if fixed on ends. First in plane blade bending, blades 1 & 2 move toward each other, blade 3 moves to the side toward which tower is bending	7.381 Hz 1.086%	7.87 Hz 1.14%
Tower bending fore-aft as if fixed on ends. Second out of plane blade bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 1 & 2 come together, blade 3 low in plane motion.	8.935 Hz 1.269%	8.68 Hz 1.33%
Second in plane blade bending, blades 1 & 2 towards each other. Blade 1 second out of plane bending. Boom up & down, nacelle pitch.	11.17 Hz 0.894%	
Second out of plane bending, blades 1 & 2 asymmetric, blade 3 in torsion		12.12 Hz 0.49%
Third out of plane bending, blades 1 & 3 symmetric, blade 2 out of phase. Boom side to side bending and nacelle yaw.	12.341 Hz 1.137%	
Nacelle pitch. Second out of plane bending, blades 1 & 2 symmetric, blade 3 out of phase. First in plane bending, blades 1 & 2 move toward each other, blade 3 low in plane motion.		13.33 Hz 1.00 %
Third out of plane bending, blade 1 & 2 symmetric, blade 3 out of phase. Boom up & down bending out of phase with nacelle pitch	14.172 Hz 0.973%	
Fourth flap blade bending, blades 1 & 2. Blade 3 in torsion, coupled with local flow angle flag devices' local modes.	17.394 Hz 0.847%	
Second tower side to side. Second out of plane bending, blades 1 & 2 symmetric, blade 3 out of phase		17.93 Hz 1.14%